

## CRITICAL ISSUES FOR FUNCTIONALLY GRADED MATERIAL DEPOSITION BY LASER ENGINEERED NET SHAPING (LENS™)

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### Abstract

Direct laser metal deposition processing has been shown to be a promising rapid manufacturing technology that has the potential to reduce the time from initial concept to finished part. One of the unique capabilities of most direct laser metal deposition processes is the ability to exploit the fact that build material is delivered to the weld pool via a powder stream. This fact allows one to perform real-time adjustments to the mixture of the powder entering the molten pool thus altering the deposited material's composition. The ability to "pick-and-place" material compositions is seen as one of the key benefits of the direct laser metal deposition technologies, enabling designers to tailor localized material characteristics within a part to best meet the design's criterion. The ability to selectively apply different material compositions at user defined regions of a build requires a thorough understanding of the dynamics of the given process and specific system. This paper will discuss a variety of those issues, as well as provide some tests that can be performed to characterize a system to enable successful building of metal parts consisting of composite and graded material regions.

### Introduction

Direct laser metal deposition processing has been shown to be a promising rapid manufacturing technology that has the potential to reduce the time from initial concept to finished part. One of the unique capabilities of most direct laser metal deposition processes is the ability to exploit the fact that build material is delivered to the weld pool via a powder stream. This fact allows one, through judicious use of hardware and software controls, to perform real-time adjustments to the mixture of the powder entering the molten pool and, thus, alter the deposited material's composition [1]. The ability to "pick-and-place" material compositions is seen as one of the key benefits of the direct laser metal deposition technologies, enabling designers to tailor localized material characteristics within a part to best meet the design's criterion. (For example, in an injection mold, a hard tool steel may be selectively placed in regions where excessive wear would be an issue, yet the bulk of the mold could be made of a material with a better coefficient of thermal conduction.)

The specific laser metal deposition technique used for this study is the Laser Engineered Net Shaping (LENS<sup>TM</sup>) process [2-6]. Figure 1a shows a schematic of the LENS<sup>TM</sup> process. A component is fabricated by creating a molten pool through focusing a laser beam onto a substrate. Metal powder particles are simultaneously injected into the pool to add material. Using computer control, the substrate is moved beneath the laser beam in the X-Y plane, depositing a thin cross section of predetermined CAD generated geometry. After deposition of a layer, the deposition head (consisting of a powder delivery nozzle and focusing lens assembly) is incremented in the positive Z-direction, allowing generation of the next layer of the part. Deposition of layers is repeated until the desired three-dimensional component has been layer additively formed. Figure 1b shows the deposition of a single pass wall in 316 stainless steel. LENS<sup>TM</sup> components have been fabricated from various alloys including stainless steels, tool steels, nickel-based super alloys, and Ti 6Al-4V.

While inherent in the LENS<sup>TM</sup> technology (as well as most other laser based metal deposition processes), the ability to selectively apply different material compositions at user defined regions of a build requires a thorough understanding of the dynamics of the given process and specific system, including aspects varying from the powder feeder, to feedback control, to elements as basic as the lengths of tubing used to carry powder from the feeder to the deposition head itself. This paper will discuss a variety of those issues, as well as provide some basic and not so basic tests that can be performed to properly characterize a system to enable successful building of metal parts consisting of composite and graded material regions.

#### Differences Between Composite and FGM Build Styles

Depending on the design criterion of a part, there are two distinct techniques through which one can vary material composition using the LENS<sup>TM</sup> process – through composite material deposition and through functionally graded material (FGM) deposition. On the surface these distinct build styles may appear similar; however, the fundamental system requirements and build approach vary dramatically. While the differences between styles will be covered in depth throughout the remainder of this paper, the basic difference, as shown in Figure 2, amounts to whether the powder remains constant for distinct build regions (composites), or whether the powder composition is continually changing (FGMs). For composites, as shown in Figures 2b and 2c, the different regions may be drawn in series, which allows the powder feeders to be set to establish the desired powder ratio prior to each composition's deposition. FGMs require the ability to change powder compositions on-the-fly, thus requiring much heavier

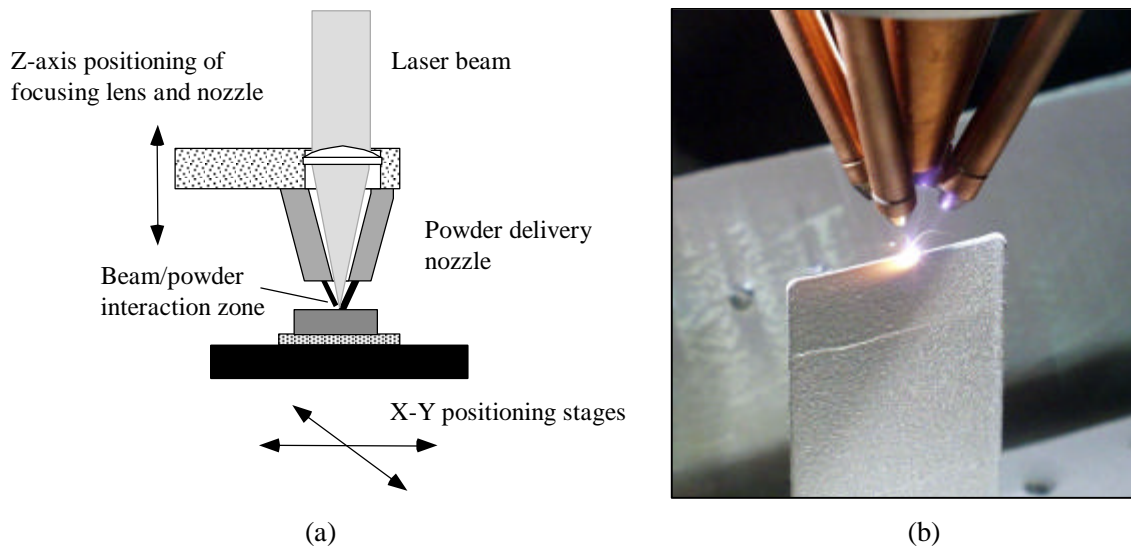


Figure 1: (a) Schematic of the LENS<sup>TM</sup> process. (b) In-situ wall fabrication.

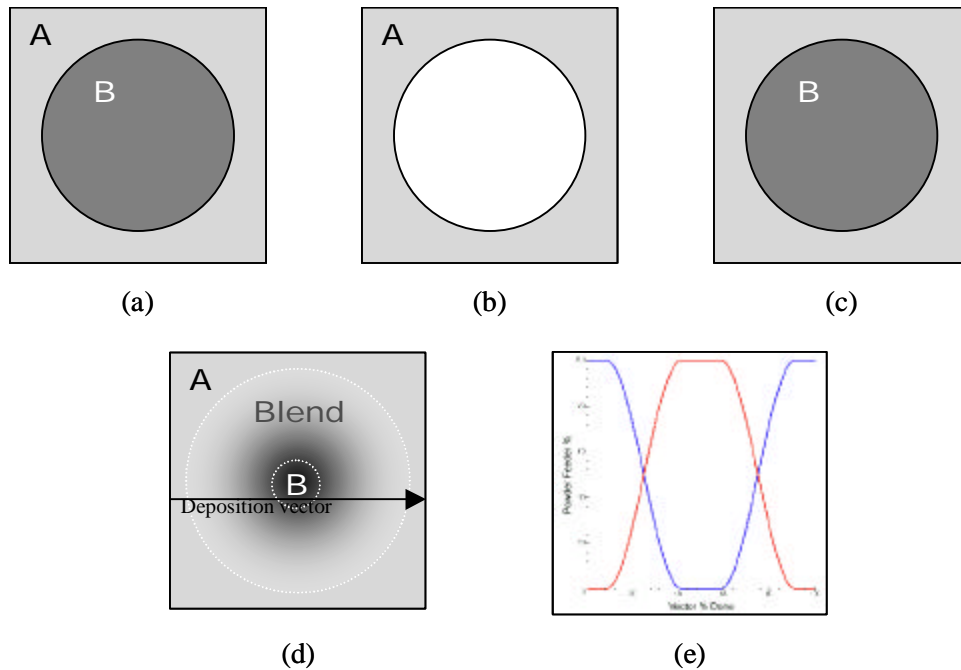


Figure 2: (a) A composite consists of distinct regions of A and B (b) Composites may be constructed by first drawing all of region A and then (c) drawing all of region B, allowing the powder feeders to be reconfigured between compositions. (d) FGMs require the powder to be continually varied throughout the build. (e) each deposition vector in an FGM build will have a unique powder feeder profile.

interaction between the powder feeder controller and the LENS<sup>TM</sup> motion controller. To further complicate the FGM issue, each vector will typically possess a unique powder profile. For example, consider the simple blend shown in Figure 2d. One deposition vector used during material deposition is shown. The powder profile required for this specific vector is shown in Figure 2e, and will differ from deposition vectors that occur at locations just above or just below the given vector.

From the previous definition, on a three axis system, all FGM deposition occurs in the XY plane. While material can be graded along the build axis (typically Z), this type of grading is properly viewed as a composite structure, since each layer is produced using a “static” powder composition. (Note that composites may consist of any desired mixture of materials available from the powder feeders – the distinguishing criterion is that the composition remains fixed during any given region’s deposition.) The distinction between composites and FGMs is important because of the level of complexity required of the control schemes for each. For composites, the chief criteria for successful deposition is that the powder feeders are well characterized, and that they may be configured to provide the desired powder composition for a given period of time. Issues involving transition times between material compositions are relegated to secondary concerns, since the system can effectively pause long enough for powder compositions to be altered and reach steady state. For FGMs, the time lag between asking for a given composition and when that composition is actually injected into the molten pool becomes critical, since the powder is continually being altered. This is further complicated by the relatively significant time lag from when powder leaves the feeder to when it reaches the deposition head.

#### Powder Feeder Characterization

The first key to the generation of both composites and FGMs is proper characterization of the powder feeder mechanism. While the following techniques are general in nature, characterization must be

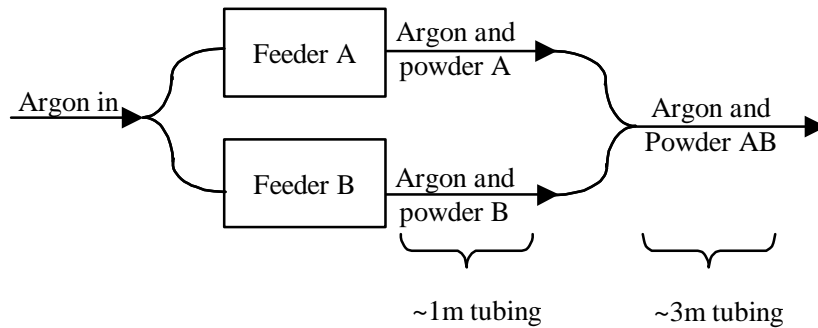


Figure 3: Powder feed system schematic of system used for experiments. Mixing of powders A and B occurs during final 3 meters of tubing prior to exiting from deposition head.

performed on each system due to every LENS™ system's unique set up (feeder, screw, powder, feed line lengths, etc.)

The feed system used for these studies is a screw-feed device that uses an open-threaded shaft to meter powder into an argon carrier gas stream (powder is transported from a powder hopper to the gas stream in a manner analogous to grain being fed through an auger). For the tests discussed in this paper and as shown in Figure 3, two feeders were placed in parallel. A single carrier gas line is divided into two distinct flows, passed through the feeders and then recombined into a single line. Mixing of the two powders occurs naturally in the re-joined argon stream.

While the screw-feed design of the feeders provides for a very linear and repeatable mass vs. RPM feed rate curve, the design does allow for some powder leakage to occur, resulting in a feed rate curve which, while linear, is offset slightly from the desired 0 RPM = 0 g/min intercept. While this perturbation does not affect the ability to create most desired composition ratios, it does limit the ability to create ratios on the low and high ends (i.e. 0:100 through 5:95 and 95:5 through 100:0) and is an issue requiring further investigation. Note that, while the feeders under question provide a linear control-signal (i.e. rpm) vs. mass flow rate curve, any appropriate feeder that provides a non-pulsed, consistently repeatable flow rate can be utilized, with any non-linearities being compensated for in the material control algorithm.

After characterizing the powder flow itself, the first experiment performed was to verify that a preset material ratio provided by the feeders actually resulted in a material deposit with that given ratio. To test this hypothesis, a simple composite column was constructed using H13 and M300 steel alloys, with the material composition of the individual layers being altered by 10% every 0.120" (i.e. 0-0.120" was 100% H13, 0.120-0.240" was 90% H13:10% M300, 0.240-0.360" was 80% H13:20% M300, etc.). (these materials were chosen for their compatibility across the blended regime as well as their distinguishable elemental constituents.) Sufficient dwell time was incorporated between material compositions to ensure stability of the new mixtures. This column was then polished and underwent material evaluation using standard microprobe techniques. Eleven elements were considered during analysis. The data revealed that the input ratios did produce the expected material compositions; all blends were within 2% of expected. Results of the nickel trace are shown in Figure 4. It should be noted that when adjusting material composition, the inter-mix transition zone is comprised of just slightly more than one layer; this is expected since to create each layer, a fraction of the previous layer must be melted to form the molten pool.

With confirmation that material composition can be controlled directly through powder feed rate, the ability to deposit composite structures is reduced to an issue of software control and path planning, where the path planning software is only required to identify and separate regions of different material

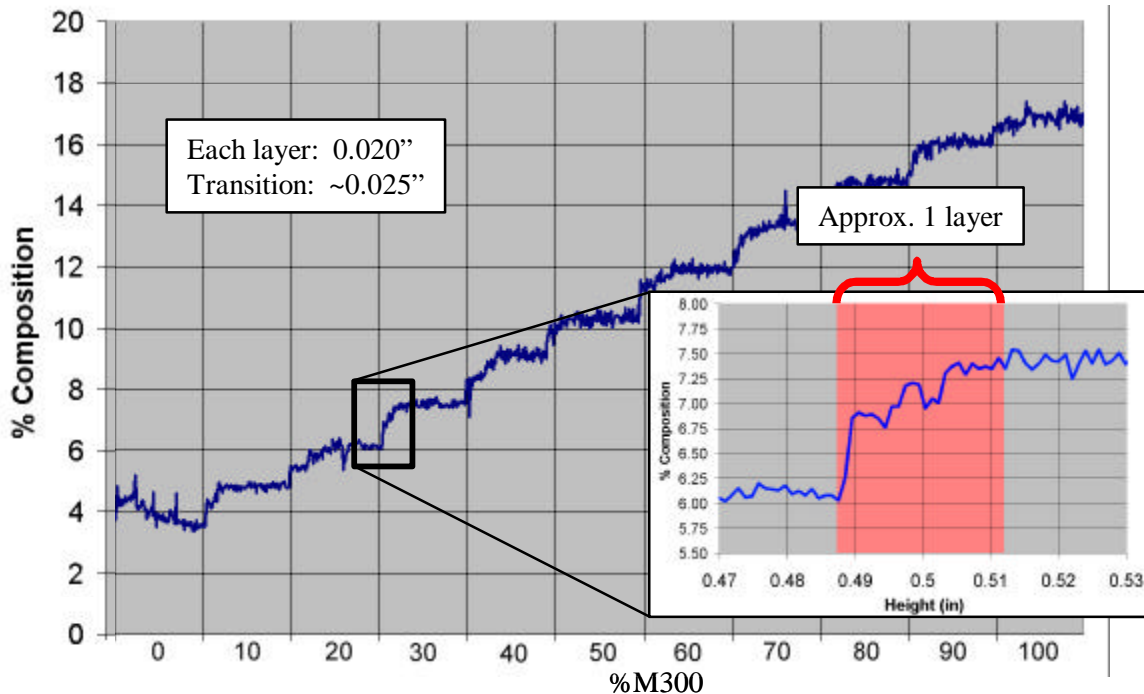


Figure 4: Nickel composition of composite structure varying between 100% H13 and 100% M300.

composition. Control simplifies the ability to set the powder feed mechanisms to the necessary flow rates for each region while ensuring long enough pauses to guarantee the purity of the new powder mixture before instigating deposition. However, this brings up the question of how long must this pause be?

Powder feed response was evaluated through the construction of a simple wall build (a single vector repeatedly drawn on top of the previous vectors). The test comprised of inducing a step change in material composition during the wall build and then, as with the previous test, using microprobe data to determine the distance (and hence time) required to fully transition from one composition to another. As before, H13 and M300 were used. Due to the nearly four meters of tubing through which the powder must flow to traverse from the feeder to the molten pool, a significant delay is to be expected before the change is seen. Furthermore, when adjusting powder ratios, the powder mixture of the earlier composition which is traveling at slower rates near the boundary layers of the tube is expected to influence the settling time.

Figure 5 shows results from three elemental microprobe traces. By correlating the distance along the measured sample with the build speed, both the initial lag as well as the settling time for this step test can be readily determined. As shown in the figure, the initial lag is approximately 0.8 seconds, with a settling time nearly three times as long, at approximately 3.1 seconds. From these results, it can be determined that pauses of greater than four seconds between material compositions should be adequate to properly adjust between compositions.

These results also bring up significant challenges for the generation of FGMs. Specifically, there is nearly a one second delay between the powder feed rate changing and the first hints of change at the molten pool. Combining this with the significant settling time requires that, during deposition, the powder control system continually and accurately predicts the future position of the molten pool; this prediction allows the powder controller to “load” the powder stream with the correct composition in order for the molten pool to receive the desired composition at the correct geometrical locations. This task is further complicated by the fact that the velocity profiles of the deposition can be heavily influenced

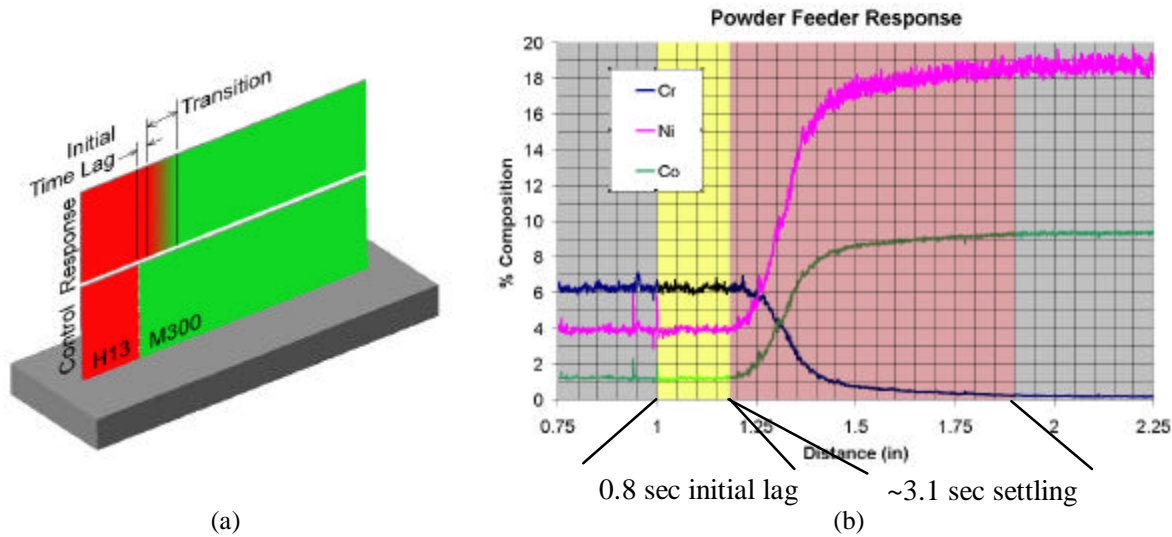


Figure 5: (a) Step response test from H13 to M300 compositions. (b) Response shows both initial time lag for new powder mixture to reach weld pool as well as significant settling time.

through outside sources during the course of a build – such influences range from the operator speeding up or slowing down build vector velocity parameters to closed loop control systems which independently control the velocity in order to affect build height and weld pool dimensions [7]. The other challenge for FGM generation is determining exactly what dwell is best applicable. Since a simple step change takes upwards of four seconds to settle out, what dwell is best utilized when the powder ratios are not experiencing a simple step change, but rather are continually being adjusted according to the non-trivial profiles as seen in Figure 3?

To investigate these issues, another test was developed, whereby a square clad was deposited onto a substrate. As shown in Figure 6, the clad was deposited using rasters angled at  $45^\circ$ , and with a powder profile designed to yield a part which linearly grades from 100% M300 along the left border to 100% H13 along the right border. The angled raster profile, in conjunction with the FGM direction, results in unique powder profiles for each deposition vector. From the microprobe results, it is then possible to “back-out” the dwell error. For this study, an initial dwell time of 2.5 seconds, based on the wall step test, was used.

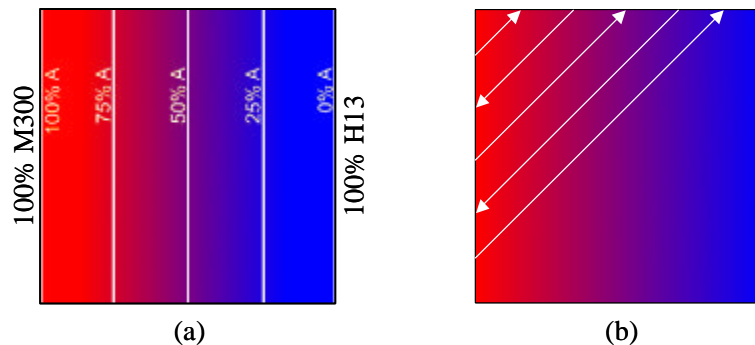


Figure 6: Clad test. (a) Material transitions from 100% M300 on left to 100% H13 on right. (b) Material is deposited using rasters angled at  $45^\circ$ , resulting in unique powder profile curves for each raster vector.

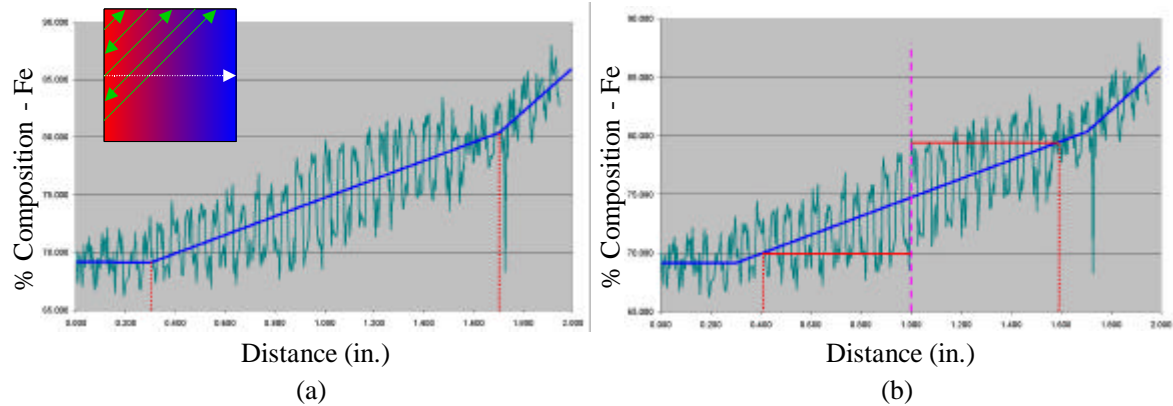


Figure 7: (a) Microprobe trace for Fe going from left to right across graded sample. Heavy line is “average” of trace. Line breaks in average are caused by insufficient dwell time. Based on the distance of the break, the appropriate dwell can be determined. (b) What appears to be noise in the microprobe trace is actually an artifact of the dwell error revealed by the raster deposition pattern. The peaks and valleys of this periodic structure can be related back to the “average,” yielding additional information about the appropriate dwell times.

The microprobe trace for iron is shown in Figure 7. This trace was taken across the middle of the clad sample, progressing from left to right as shown in the insert in Figure 7a. The heavy line overlaying the data in the left graph is the “average” value of the microprobe trace. Of note are the two distinct breaks in the average line. These breaks are a direct result of the 2.5-second dwell used during deposition being insufficient. By taking into consideration the deposition velocity (20 in/min), the distances to these breaks (0.3 in) can be used to calculate the additional dwell necessary (1.8 sec.).

The “noise” which occurs in the microprobe data can also be used to confirm the additional dwell time required. What appears to be noise is, in actuality, an artifact of the dwell error revealed through the angled raster deposition pattern. When depositing from lower left towards the upper right, the dwell error causes the material ratio to lag behind what is expected (the “average” line). The same is true when the raster reverses itself and deposits from upper right towards lower left. The microprobe trace “cuts” across this repeating pattern, resulting in the periodic trace seen in Figure 7a.

The graph of Figure 7b shows how these peaks and valleys can be used to further confirm the necessary dwell values. By tracing from a peak across to the expected “average” line, the error is revealed as a distance. As with the line breaks discussed in left graph of Figure 7, this distance can be converted to time through knowledge of the deposition velocity. The valleys can be treated in the same fashion. For the test in question, the distance calculated from the peaks and valleys to the average is approximately 0.6 in. At 20 in/min deposition rate, this reveals the dwell error to be approximately 1.8 seconds – the same error as shown through analysis of the breaks in the average.

Taking into consideration the 2.5-second dwell initially used for the clad test, the total dwell time necessary for this specific powder feed configuration is therefore shown to be approximately 4.3 seconds. Relating this value back to the step test results shown in Figure 5 reveals that the driving factor controlling the deposited composition for FGMs is the settling time rather than the rise time.

### Conclusions

This series of studies looked at techniques to characterize a powder control system to the extent necessary to enable the development of laser deposited composite and FGM structures. Key components of this characterization are development of the traditional control signal vs. flow rate curve, verification that the

deposited material is a direct reflection of the powder feed settings, and determination of the dwell time inherent in transporting powder from the feeder to the molten pool. Through a series of simple deposition studies, coupled with appropriate microprobe analysis, generalized techniques were developed which both verified the relationship between powder feed and actual deposition, as well as established the governing dwell times associated with the powder transport. Once determined, these values may be readily fed into the powder feed software control scheme, providing the necessary functionality required for the creation of both composite material and functionally graded material depositions.

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#### References

1. M. L. Griffith, L. D. Harwell, J. A. Romero, E. Schlienger, C. L. Atwood, J. E. Smugeresky, "Multi-Material Processing by LENS", *Proceedings of the Solid Freeform Fabrication Symposium*, August, 1997, Austin, TX, p.387.
2. M. L. Griffith, D. M. Keicher, C. L. Atwood, J. A. Romero, J. E. Smugeresky, L. D. Harwell, D. L. Greene, "Free Form Fabrication of Metallic Components using Laser Engineered Net Shaping (LENS)", *Proceedings of the Solid Freeform Fabrication Symposium*, August 12-14, 1996, Austin, TX, p. 125.
3. D. M. Keicher, J. A. Romero, M. L. Griffith, C. L. Atwood, "Laser Metal Deposition of Alloy 625 for Free Form Fabrication", *Proceedings of the World Congress on Powder Metallurgy and Particulate Materials*, June 16-21, 1996, Washington, D.C.
4. John E. Smugeresky, Dave M. Keicher, Joseph A. Romero, Michelle L. Griffith, Lane D. Harwell, "Using the Laser Engineered Net Shaping (LENS) Process to Produce Complex Components from a CAD Solid Model", *Photonics West SPIE Proceedings - Lasers as Tools for Manufacturing*, Volume 2993, 1997, p. 91.
5. E. Schlienger, D. Dimos, M. Griffith, J. Michael, M. Oliver, T. Romero, J. Smugeresky, "Near Net Shape Production of Metal Components using LENS", *Proceedings of the Third Pacific Rim International Conference on Advanced Materials and Processing*, July 12-16, 1998, Honolulu, HI, p. 1581.
6. C. L. Atwood, M. L. Griffith, M. E. Schlienger, L. D. Harwell, M. T. Ensiz, D. M. Keicher, M. E. Schlienger, J. A. Romero, J. E. Smugeresky, "Laser Engineered Net Shaping (LENS): A Tool for Direct Fabrication of Metal Parts", *Proceedings of ICALEO '98*, November 16-19, 1998, Orlando, FL, p. E-1.
7. W. Hofmeister, M. Wert, J. Smugeresky, J.A. Philliber, M. Griffith, and M. Ensiz, *JOM*, Vol. 51, No. 7, available from JOM-e online at [www.tms.org/pubs/journals/JOM/9907/Hofmeister/Hofmeister-9907.html](http://www.tms.org/pubs/journals/JOM/9907/Hofmeister/Hofmeister-9907.html).